

Wireless lysimeters for real-time online soil water monitoring

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Abstract Identification of drainage water allows assessing the effectiveness of water management. Passive capillary wick-type lysimeters (PCAPs) were used to monitor water flux leached below the root zone under an irrigated cropping system. Wireless lysimeters were developed for web-based real-time online monitoring of drainage water using a distributed wireless sensor network (WSN). Twelve PCAP sensing stations were installed across the field at 90 cm below the soil surface, and each station measured the amount of drainage water using two tipping buckets mounted in the lysimeter and continually monitored soil water contents using two soil moisture sensors installed above the lysimeter. A weather station was included in the WSN to measure micrometeorological field conditions. All in-field sensory data were periodically sampled and wirelessly transmitted to a base station that was bridged to a web server for broadcasting the data on the internet. Communication signals from the in-field sensing stations to the base station were successfully interfaced using low-cost Bluetooth wireless radio

communication. Field experiments resulted in high correlation between estimated and actual drainage with $r^2 = 0.95$ and confirmed a reliable wireless communication throughout the growing season. A web-linked WSN system provided convenient remote online access to monitor drainage water flux and field conditions without the need for costly time-consuming supportive operations.

Introduction

Lysimeters have been widely used for water quality studies to measure drainage water below the root zone and determine the movement of chemicals in the soil profile (Klocke et al. 1993; Owens 1990; Shukla et al. 2006; Syvertsen and Smith 1996). Studies have reported that a passive capillary wick lysimeter (PCAP) offers better estimates of actual soil water drainage fluxes than alternative field methods (Gee et al. 2002; Jabro et al. 2008; Louie et al. 2000), as they require no external vacuum devices to extract soil pore water under unsaturated conditions (Boll et al. 1992; Czigany et al. 2005; Zhu et al. 2002). The development of a web-based remote monitoring system of the lysimeters using wireless sensor network provides real-time online access to the lysimeters and helps growers enhance productivity and water management without the need for costly time-consuming supportive operations (Jabro et al. 2008). However, seamless integration of sensor network, data interface, and wireless communication is challenging.

A wireless data communication system offers dynamic mobility and easy relocation benefits, while a hard-wired system takes extensive time and cost to install and maintain and may not be acceptable to growers due to its interference with normal farming operations. Bluetooth wireless technology has been widely adopted in consumer products and

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provides opportunities to apply wireless communication in agricultural systems (Lee et al. 2002; Oksanen et al. 2004; Zhang 2004). Oksanen et al. (2004) used a personal digital assistant (PDA) equipped with Bluetooth to connect a global positioning system (GPS) receiver for their open, generic, and configurable automation platform for agricultural machinery. Zhang (2004) evaluated Bluetooth radio for different agricultural environments, power consumption, and data transmission rates. He observed 1.4 m as an optimal radio height for a maximum 44-m radio range and reported limitations of significant signal loss after 8 h of continuous battery operation and 2–3 s of transmission latency with the increase in communication range. Lee et al. (2002) explored an application of Bluetooth wireless data transmission of the moisture content of harvested silage and reported a limitation of a short 10 m range. However, the limitations reported can be solved or minimized by system design optimization; power shortages can be solved by using solar panels that recharge the battery, and the radio range can also be improved by upgrading the power class and antennas.

Wireless sensor networks (WSN) have been investigated for the potential use of various sensing and control applications. Soil moisture data were wirelessly sent from dataloggers to a remote computer via radio transmission by Kim et al. (2008) and Shock et al. (1999). Others proposed architectures of distributed sensor networks for automation of site-specific irrigation systems (Kim et al. 2009; Wall and King 2004). Few have fully integrated wireless sensor technology into real-time online access. The objective of this paper is to present details of the design, installation, and evaluation of an integrated, distributed WSN of in-field lysimeters for real-time online remote access using Bluetooth wireless technology.

Materials and methods

Lysimeter design

Twelve PCAPs were constructed from plastic (HyTEK, Corvallis, OR), and the outside box was sized to 91 cm (L) × 31 cm (W) × 87 cm (H), as shown in Fig. 1. A shelf was mounted horizontally inside the box at 15 cm above the bottom of the box and with a grid of 6-mm-diameter holes for water drainage (Fig. 1a). Two tipping buckets were fastened to the shelf and collected drainage water through wicks on the top of the box. The shelf also had a 38-mm-diameter hole in the middle of the shelf to hold an 18-cm length glass tube that was held in place by a rubber stopper, staying 13 mm off the bottom of the box. High-purity plastic tubing was attached to the glass tube, through which drainage water is pumped out of the box for further analysis.

The top of the box had three holes with 38 mm diameter each. Five wicks were located in each of the outer two holes with tubing, and wires were routed through the middle hole. Prior to installation, the wicks were cleaned, rinsed with triple distilled water, and then air-dried at room temperature (Jabro et al. 2008). Each wick was 122 cm in length with 76 cm of wick going into the tipping buckets. The remaining wick on the top of the box was unraveled and evenly distributed to cover the top surface of the box. Two wires from the tipping buckets and the plastic water tube were strung through a conduit that was attached on the top of the box and connected to a datalogger enclosure. Each lysimeter was installed 178 cm below the soil surface (Fig. 1b) and covered by soil that was packed and leveled using a soil compacter machine. Further detailed information regarding design, construction, installation, and performance of the PCAPs can be found in Jabro et al. (2008).

Wireless sensor network (WSN) design

A layout of the distributed in-field WSN is illustrated in Fig. 2. The network consists of twelve lysimeter sensing stations, a weather station, and a base station. The twelve lysimeters were evenly distributed across the experimental field of 72 plots (each 15 × 24 m) arranged in a 4 × 18 matrix, as shown in Fig. 2. All data from the lysimeters and weather station are wirelessly transmitted to the base station that is linked to a web server to upload graphical display of the data on the internet. The in-field sensing stations contain three main parts in system design and integration: data acquisition, wireless data communication, and power management.

Data acquisition

In-field lysimeter data were logged by a datalogger (CR200, Campbell, Logan, UT) at each sensing stations, whereas weather data were logged by a datalogger (CR10, Campbell, Logan, UT). All dataloggers are self-powered by a solar panel (SX5, Solarex, Sacramento, CA) that recharges a 12 V battery (NP7-12, Yuasa, Laureldale, PA) (Fig. 3). Two time-domain reflectometers (CS625, Campbell, Logan, UT) were horizontally installed at 15 cm and 76 cm soil depths, respectively, and continuously monitored volumetric soil water contents by the shallow and deep root zones (Fig. 1b). Drainage water amount was recorded at pulse counters from two tipping buckets mounted in the lysimeter box. A program was coded in application software (CRBasic, Campbell, Logan, UT) to scan two soil water sensors and two tipping buckets.

The weather station recorded micrometeorological information on the field, i.e., air temperature, relative

Fig. 1 Schematic diagram of lysimeter design: **a** box design and installation of tipping buckets and wicks, **b** installation of the lysimeter box and two soil moisture sensors at 15 and 76 cm depth

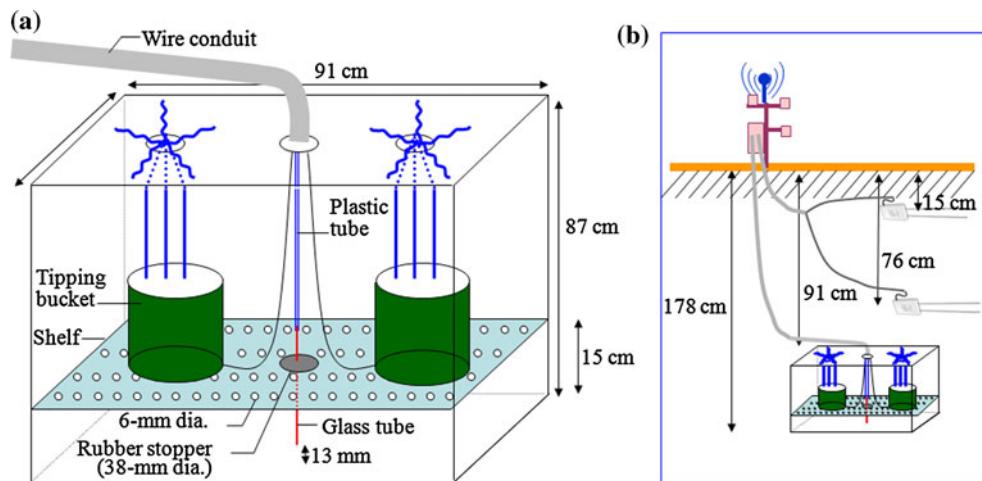


Fig. 2 Layout of in-field wireless sensor network for real-time online monitoring of twelve lysimeters and an in-field weather (background photo from Google map)

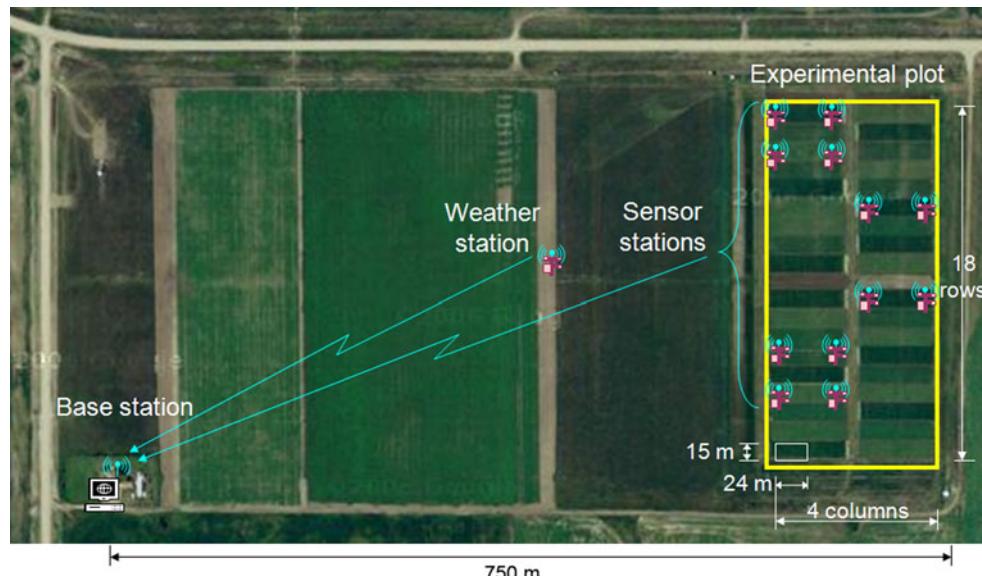
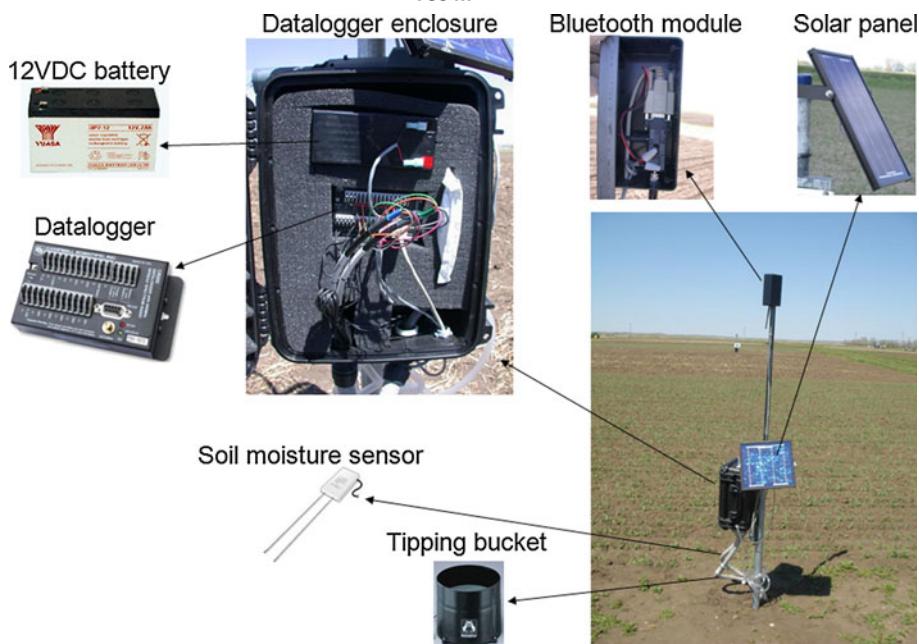


Fig. 3 System components of the lysimeter sensing station



humidity, soil temperature, precipitation, wind speed, wind direction, and solar radiation. A temperature probe (107, Campbell, Logan, UT) measured soil temperature at the 5- and 20-cm soil depths. Air temperature and humidity were measured by a humidity probe (HMP35C, Vaisala, Helsinki, Finland) mounted at the 2 m height above the ground with a solar radiation shield. A generic tipping bucket was used to measure precipitation. Wind speed and direction were measured at 2 m from the ground by a wind sensory set (03001, R.M. Young, Traverse City, MI). A pyranometer (LI200X, Licor, Lincoln, NE) was horizontally leveled and provided measures of solar radiation as total flux and flux density.

The program for the weather station was coded in another programming application (Edlog, Campbell, Logan, UT) as it uses a different datalogger (CR10). Cumulative precipitation was calculated in the program and automatically reset to zero every midnight. All dataloggers for both lysimeter stations and weather station used in this study were programmed to read data at the same time at 10-s scanning rate and wirelessly transmit the sensory data to the base station every 15 min.

Wireless data communication

The selection of wireless communication protocol was determined by considering distance, data rate, compatibility, and cost. For the application in this study, the field was located approximately 750 m from the base station, and the data volume to transfer was less than 1 KB per cycle in both transmitting and receiving processes. Based on consideration of accommodating existing dataloggers, and compatibility to RS-232 serial communication devices, and cost-effective wireless network, a Bluetooth radio module (SD205, Initium Co., Sungnam, Korea) was selected for the wireless data communication, as it features robust signal connectivity, low cost (US \$129), and communication range up to 1,200 m with a patch antenna (IA60-802). This radio module is equipped with power class 1 (63 mW) with maximum data transfer rate of 380 Kbps and interfaced with a 9-pin D-sub female connector and an antenna port and powered by 5–12 VDC with current draw of 66 mA at 9,600 bps data rate (Initium Co 2005). The Bluetooth radio antenna of the in-field sensing stations was mounted approximately 2 m above the ground.

Two Bluetooth master receivers (MSP-102a, Initium Co., Sungnam, Korea) mounted on the base station wirelessly received data from all in-field sensing stations and sent the data to the base computer via TCP/IP (transmission control protocol/internet protocol) Ethernet. Each of thirteen Bluetooth slave modules was registered into a unique TCP data port and associated with a serial port. As one master receiver is capable of pairing with a total of seven

slave modules, thirteen Bluetooth slave modules were paired with two master receivers and identified by the different IP and TCP port numbers.

Power management

The long-term operation of a self-powered wireless system requires efficient power management for wireless data transmission. Power consumption was estimated based on two modes: stand-by mode that draws power to maintain signal connection and active mode that draws more power to execute signal transmission. With a scanning interval of 10 s and data transmission interval of 15 min, the daily total power consumption was 23.8 Wh/day. The majority of power was consumed in a stand-by mode of the Bluetooth module. The total power supply from a battery (12 V, 7 Ah, 1.75 A max) and solar panel (max. 4 W with estimated average sunlight 5 h/day) was 84 and 20 Wh, respectively. This indicates the proposed power system can last only about 3.5 days if there is no enough sunlight such as rainy or cloudy days. Thus, power management for the wireless data communication was redesigned to change the stand-by mode to a sleep mode, which can save up to 80% (19 Wh/day) of daily total power consumption.

In order to selectively turn the power on and off, a Bluetooth power cable was connected to a switched battery port (CR200 datalogger) for the lysimeter sensing stations and a control port (CR10 datalogger) for the weather station through a custom-designed inverted switch circuit by using a NPN bipolar Darlington transistor (NZT5073). A datalogger program was modified to trigger the port that provides Bluetooth power for 2 min. The first minute allows a wake-up signal to stabilize connectivity, and the second minute provides for data transmission. The radio signal connectivity is monitored by Bluetooth software (Promi-MSP, ver. 2.5, Initium Co., Sungnam, Korea).

Online real-time monitoring

The base computer is linked to a web server for real-time online data display. The data storage and retrieval are configured in the base computer by application software (LoggerNet, Campbell Scientific, Inc., Logan, UT) that uses client–server architecture. The server software runs in the background handling all of the datalogger communications, while the client applications connect to the server to access the information collected from the dataloggers. A web server client (RTMC Web Server, Campbell, Logan, UT) is used to display real-time data in an HTML (hypertext markup language) format and allows real-time data display to be shared via internet web browsers. The HTML file created by the client displays the most recent data in any of the datalogger tables in the sensor network as

well as data browser and network status. The web server was set to a 1-min update interval and 100 for the HTTP (hypertext transfer protocol) port. To view web pages of the lysimeter data from the web server, the URL (uniform resource locator) for the web server is entered on a web browser application.

Water flux sampling

The tipping bucket was calibrated to convert the number of tips to drainage water volume collected by the lysimeter. The depth conversion given by the manufacturer is 0.254 mm per tip for a 20.3-cm-diameter bucket. Thus, the volume conversion becomes.

$$\text{Bucket area (cm}^2\text{)} \times \text{depth conversion factor (cm/tip)} \\ = \pi(20.3/2)^2 \times 0.0254 = 8.237 \text{ ml/tip.} \quad (1)$$

The depth conversion for the lysimeter box per tip is further converted as

$$\text{Volume conversion (ml/tip)/lysimeter box area (cm}^2\text{)} \\ = 8.237/(31 \times 91) = 0.029 \text{ mm/tip.} \quad (2)$$

The cumulative total drainage water in the lysimeter was calculated by the sum of two pulse counters from two tipping buckets in the lysimeter.

Results

This study was conducted on a 1.4 ha, nearly level (2% slope) field at the USDA-ARS Nesson Valley Research farm located approximately 37 km east of Williston, ND (48.1640 N, 103.0986 W). The site is a new research area that has been in rain-fed hay production for over 5 years. The soil is classified as Lihen sandy loam (sandy, mixed, frigid Entic Haplustoll).

The experimental field was designed for irrigation frequency and crop rotation studies of potato, sugarbeet, and malting barley (Jabro et al. 2008). These plots were irrigated with the same amount of water on two different frequencies, high (15 mm) and low (30 mm) irrigation, with a 366-m self-propelled linear move irrigation system equipped with mid-elevation spray heads on 1.5-m spacing (Evans and Iversen 2005). Each of the 18 strips has two of the three crops and each crop was irrigated to match its respective actual evapotranspiration (ET_a) throughout the growing season. The lysimeters were located at each of the twelve plots that are generated by two crop rotation patterns and two irrigation frequencies and replicated three times. Details of plot design are found in Jabro et al. (2008).

Wireless signal connectivity

During field installation of in-field wireless sensor stations for twelve lysimeters, occasional signal interference was found at two of the lysimeter sensing stations and caused by being partially blocked by the humped ground between the base and sensing stations. Since the signal degradation was caused by their lower geographical locations, those lysimeter stations were modified to obtain a clear line of sight by raising the radio antenna height from 2 to 2.7 m with an extended mounting pole and cables. This slight change of the radio antenna height significantly improved the signal strength and completely resolved the signal disturbance. No further signal interference was found over the distance of approximately 750 m in the wireless sensor network. The self-powered batteries maintained the voltage above 12 V, and solid wireless signal connectivity was achieved throughout the entire growing season (Table 1) at all twelve stations (S1–S12) except one at station 12 (S12) that was caused by a bad battery and recovered after replacing the battery.

Real-time online monitoring

Web-based real-time online monitoring of in-field sensing stations is illustrated in Fig. 4. The battery status of all thirteen sensor stations and solar radiation is plotted on the top graph in first and second y-axes, respectively, with colored indexes as well as date and time stamps of last update at each station on the right side of the graph. Relative humidity and precipitation are illustrated on the second graph. Daily total precipitation is also plotted in the graph along with individual tip counts. Air temperature (with wind chill and dew point), soil temperatures (at the 5 and 20 cm soil depths), wind speed, and wind direction are displayed by scrolling down the screen.

Real-time online graphical displays of the lysimeter sensing stations are illustrated in Fig. 5. The top graph displays drainage water amount at each lysimeter in both forms of tip counts and cumulative total amounts. There has been no drainage water because of no rain and irrigation at the end of the growing season. Volumetric soil water contents in percent at the 15- and 76-cm soil depths are plotted in following graphs. Each graph shows three lysimeter stations and is titled with a crop type (sugarbeet or barley) and irrigation frequency (high or low) in which the station is located.

Lysimeter drainage water flux

Soil water drainage and fluxes in the vadose zone were sampled and calculated from the lysimeters in the

Table 1 Wireless signal connectivity during entire growing season: average battery power status of twelve sensor stations (S1–S12) wirelessly transmitted from in-field WSN, showing higher than

operable 12 V at all stations except one at station 12 (S12) that was caused by a bad battery and recovered after replacing the battery

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
May	13.0	13.1	13.0	13.0	13.0	12.9	13.2	13.1	13.0	13.1	13.0	12.1
Jun	12.8	12.9	12.8	12.9	12.9	12.8	13.0	13.0	12.9	13.0	12.9	11.5
Jul	12.8	12.9	12.8	12.9	12.9	12.9	13.0	13.0	12.2	12.9	12.9	8.1
Aug	12.8	12.9	12.8	12.9	12.9	12.8	13.0	12.9	12.0	12.9	12.8	8.1
Sep	12.7	12.9	12.7	12.6	12.9	12.8	13.0	12.9	12.8	12.8	12.8	12.1
Oct	12.8	13.0	12.7	12.8	12.9	12.7	13.0	13.0	12.8	12.9	12.9	12.9
Nov	12.8	13.0	12.5	12.8	12.8	12.7	13.0	13.0	12.8	13.0	12.9	12.9
Dec	12.7	12.9	12.1	12.6	12.5	12.4	13.0	12.7	12.7	12.8	12.8	12.8

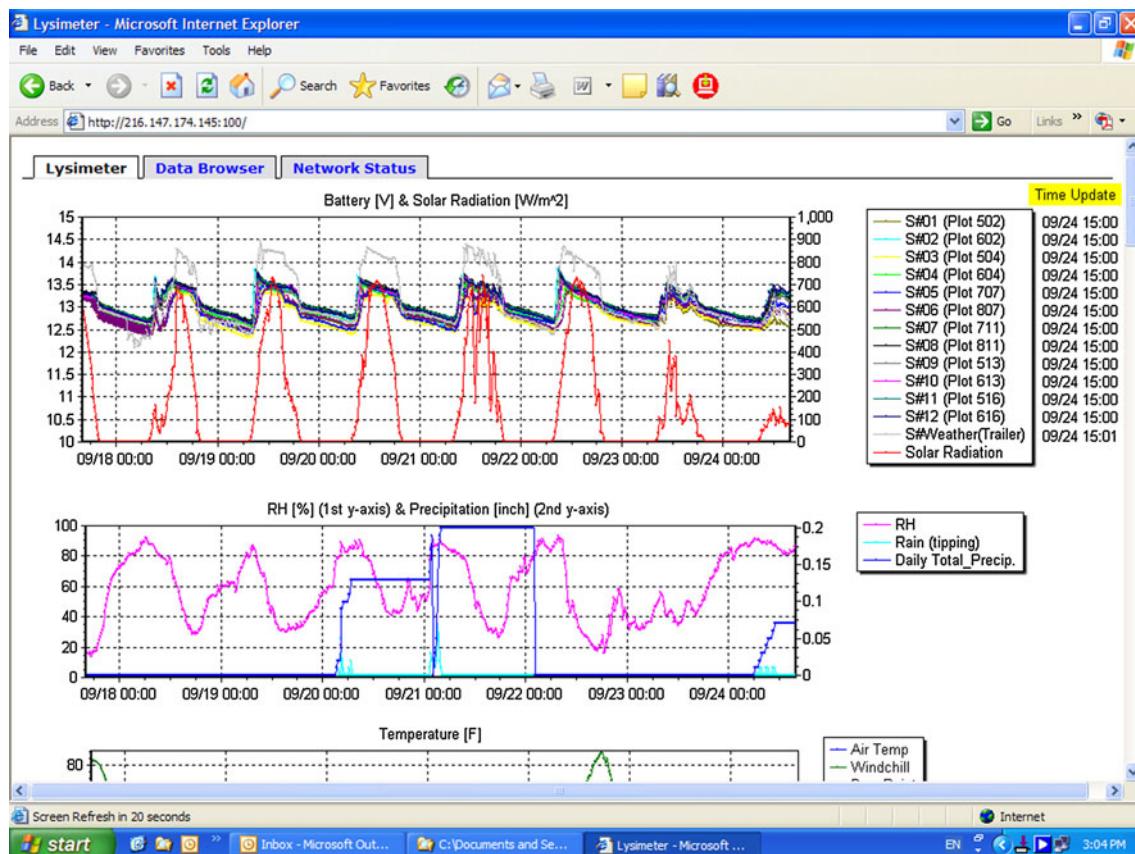


Fig. 4 Web-based real-time online display of in-field sensing stations: battery, solar radiation, and relative humidity (RH), and precipitation

sugarbeet and barley cropping systems. The automated wireless lysimeters recorded in situ measurement of drainage water and flux every 15 min and continuously estimated drainage water and flux without need for costly time-consuming supportive system such as vacuums and pumps. Actual drainage water was manually sampled by an electric pump from the lysimeters weekly from May to mid-August and biweekly thereafter. Cumulative data of estimated and actual drainage water at the sugarbeet plot under high-frequency irrigation (lysimeter station #9) are

displayed along with rainfall and irrigation in Fig. 6. Rainfall was recorded by a weather station from the WSN, and the irrigation schedule was determined by typical farm practice using evapotranspiration (ET). Drainage water was increased by rainfall in the early growing season, whereas little drainage occurred during the summer months (July and August) because of high ET rates of crops. Cumulative amount of estimated drainage water agreed with those of actual drainage throughout growing season with correlation coefficient $r^2 = 0.78$.

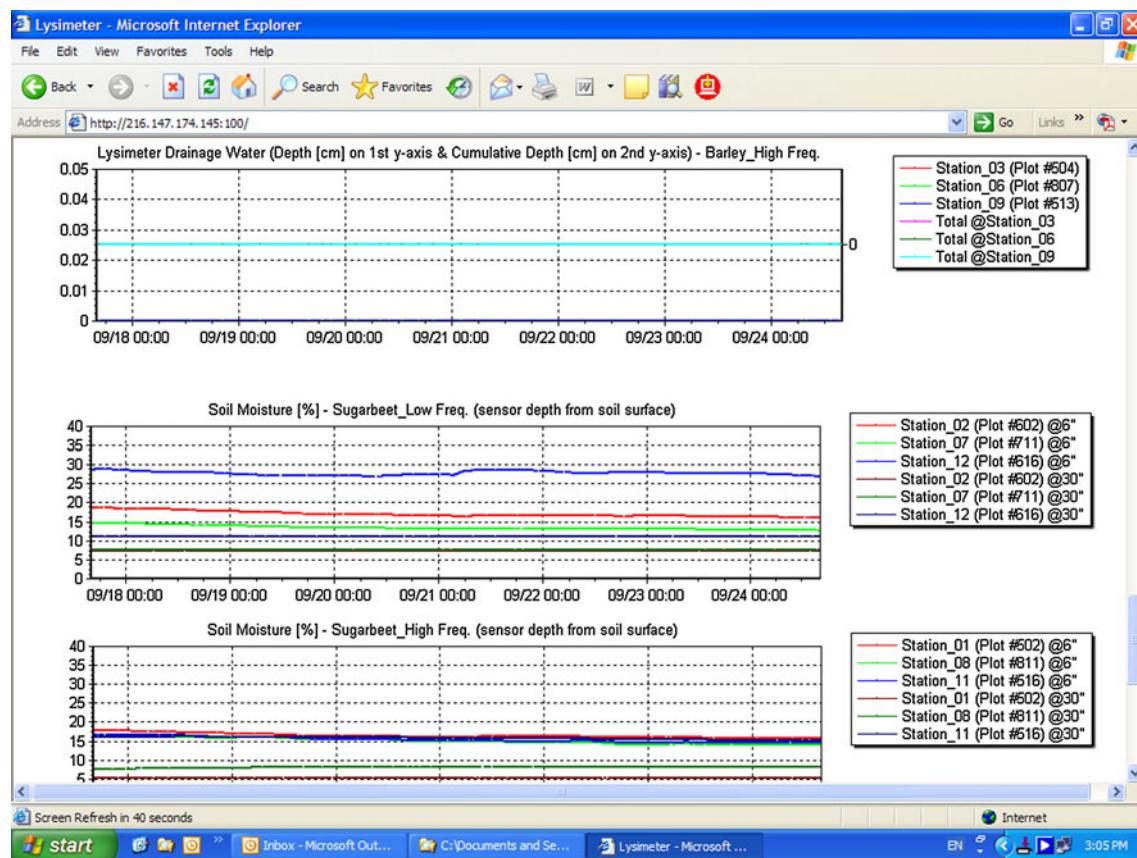


Fig. 5 Web-based real-time online display of in-field sensing stations: drainage water in the lysimeter and soil moisture at the 15- and 76-cm soil depths

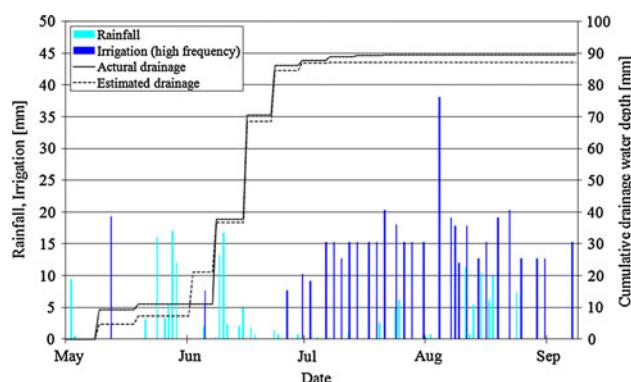


Fig. 6 WSN estimated drainage water compared with actual pumped water from the lysimeter station #9 at sugarbeet plot under high-frequency irrigation, $r^2 = 0.78$

Total drainage water estimates of all twelve stations during May through September are illustrated in Fig. 7 and compared with actual drainage at each lysimeter station. It is first noticed that rainfall or irrigation water is not uniformly drained into the vadose zone across the field. Differences in terrain elevation, soil compaction, and crop rooting systems are suspected to determine the geography of soil water drain channels in the vadose zone and thus

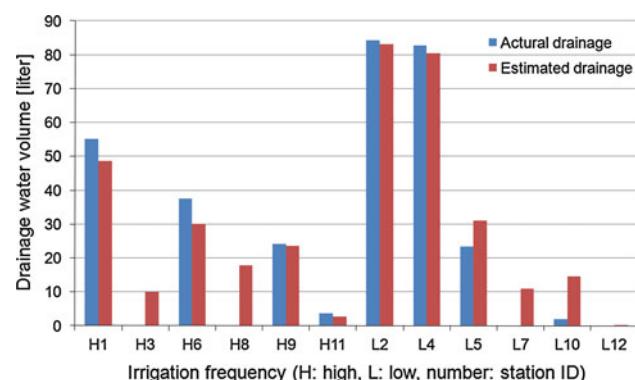


Fig. 7 Accumulated drainage water estimated by in-field wireless sensor stations during May–September compared to actual drainage water with $r^2 = 0.95$

affect the variation of drainage water in the lysimeters. The figure also shows that plots under high-frequency irrigation (six sets of bars labeled with H) have lower drainage water than those under low-frequency irrigation (six sets of bars labeled with L), because the more frequent the application, the higher the chance of losing water by evaporation and transpiration before water reaches the root zone. Overall distribution of estimated drainage water from WSN

lysimeters closely matched sampled drainage water from all twelve lysimeters with r^2 equal to 0.95.

The access to the cumulative drainage water amount allows the user to know how much water was drained in each lysimeter and helps manage the time to pump the water from the lysimeter before it is fully filled. Design improvement for maintenance and operation was detailed by Jabro et al. (2008).

Conclusions

The wireless sensor network (WSN) system with Bluetooth is a convenient and cost beneficial measurement and control tool for agricultural field. The design of distributed WSN and the result of operation in an experimental field are valuable for researchers and engineers. This paper introduced a web-based wireless lysimeter network system with details of integrated system design and documented experimental results during the entire growing season. The use of Bluetooth wireless sensing technology with lysimeters and web server enabled real-time online monitoring and measurement of drainage water and in-field weather data on the internet. Statistical results ($r^2 = 0.95$ between estimated and actual drainage) confirmed that WSN lysimeters offers a reliable and convenient way to measure drainage water volume and flux in the vadose zone without the need for time-consuming supportive operations such as vacuum and water pumping systems. A cost-effective wireless solution is a key concern to accommodate small farms and was proposed by using low-cost (approximately US \$2,000 for 13 transmitters and 2 receivers) Bluetooth wireless radio communication that offered plug-and-play communication. A durable self-powering system must be carried out in wireless sensor systems and was successfully achieved by controlling power modes between awake and sleep modes of Bluetooth radio transmitters. This study proved a concept of a promising low-cost, web-based wireless solution for online remote access to drainage water and field condition. A learning process was undertaken during the installation and operation for the WSN lysimeters and contributed to design improvements. Automated sensing and wireless technology can be extended for real-time control of farm machinery and online monitoring of farm facilities.

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